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Stirring of melt during solidification process for effective grain fragmentation using pulsed electromagnetic fields

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The paper describes the results of an experimental research, demonstrating and explaining the effect of grain fragmentation, caused by pulsed resonant electromagnetic stirring. In the experiment, 6082 aluminium alloy melt was directionally solidified under the influence of continuous and pulsed application of an alternating magnetic field (AMF). The frequency of applied pulsed field (PMF) was in accordance to the low-frequency circulation of the melt, causing the resonant increase of a pulsed component of the melt velocity. The structure of electromagnetically stirred specimens was compared to those, solidified without a magnetic field. A strong fragmentation effect (decrease of an average grain size on 51%, comparing with the solidification in natural conditions) for the case of resonant EM stirring was stated. Further, to analyse the influence of the flow, appearing due to the resonant stirring, we observed the formation of solid/liquid interface and a macro-crystalloid structure during solidification of continuously and pulsed stirred melt by applying the novel method of neutron radiography. The results confirmed the strong influence of the pulsed component of velocity on thermal conditions during solidification and, consequently, the metal structure.

Key words: *melt, electromagnetic stirring, solidification, grain fragmentation, process imaging, neutron radiography*

Introduction

Since several decades, the electromagnetic (EM) stirring of solidifying materials is known as an advanced technique for approaching metals with desired properties [1–4]. Yet still, the development of this technique is still based on trial-and-error approach, what makes new solutions applicable only for a limited number of processes and installations. Development of universal and effective method of metallic grain fragmentation and their homogenous distribution remains one of the important challenging problems.

The reason, why this problem was not solved till now, is the enormous role, which electromagnetically driven turbulent flows playing in the process of crystals formation [5], and at the same time an impossibility of performance of in-situ measurements in metallic melts, due to their opacity, chemical aggressiveness, and high melting temperature. These limitations reduce the number of methods, which could be applied for gaining the information about the interaction between turbulent melt flows and the crystallizing material.

The methods, allowing investigating these processes and broadly used nowadays are the numerical simulation and X-ray analysis. Both these methods, being quite effective, have their own disadvantages. All results obtained based on numerical simulation should have to be experimentally verified, what brings investigators back to the problem of measurements in liquid metals. From the other side, the X-ray radiography can be employed to visualize the dendritic growth of metal alloys, though the thickness of the sample under analysis strongly depends to the ray energy and usually does not exceed 1 cm for metals. Due to the high viscous properties of liquid metals development of three-dimensional turbulent flows, which have such a great influence on crystal formation, in such suppressed volumes is practically impossible. These circumstances force the search of technique, which could allow the in-situ observation of metal solidification process for specimens with increased volume and on-time effective correction of EM parameters.

As it has been shown by several recent experimental investigations, the neutron radiography can be applied to solidifying material for such a visualization [6, 7]. Now, when the technology allows employing the method of neutron radiography to close-to-industrial processes, it is more than important to collect the visual information about the interrelated phenomenon in electromagnetically stirred solidifying material with the aim to optimize the technology.

Based on the previous research, related to the optimal application of pulsed EM field (PMF) for effective grain fragmentation and redistribution, this article discusses the visualization results of the metal structure, formed under the EM treatment of the melt. The macro-crystalloid structure of ingots with increased thickness, grown under the influence of turbulent flows is analyzed. Being one of the most promising methods of EM stirring, application of resonant pulsed EM field is in the focus of the present work.

Solidification experiment with EM stirring

On the first stage of the research the solidification of 6082 aluminium alloy in different conditions was experimentally investigated. The detailed description of experimental system, the procedure of specimens post-processing and metallographic analysis can be found in previous publication [8]. In the experiment, we reproduced the operation of a continuous casting device on the limited material volume (500 g) and provided its directional crystallization with and without EM stirring by alternating magnetic field. Furthermore, the magnetic field was applied to the solidifying melt in one case permanently and in the other case with low-frequency pulses. The frequency of applied pulsed AMF was in accordance to the low-frequency circulation of the melt, causing the resonant increase of a pulsed component of the melt velocity. The structure of all obtained specimens was compared and analysed. Two main parameters were taken into account – the average size of metal grains and homogeneity of their distribution. The magnified surface of the samples middle section, grown in natural conditions and stirred by means of permanent and resonant pulsed magnetic field is presented in Figure 1.

The strong fragmentation effect was observed in the probe, stirred with resonant magnetic field – the average grain size, calculated for the investigated area was 320 мm for the natural solidification and 155 мm for EM treatment with pulses (reduction on 51%, Fig. 1, a and c). The permanent EM stirring led to grains fragmentation on 40% (187 мm, Fig. 1, b). One can notice the increased homogeneity of the structure, obtained with resonant EM stirring – comparing to other both cases, the variation of grain sizes is much lower.

The experiment has shown the strong influence of type of the melt motion on solidification conditions. In the further step of the study the model experiment, reproducing the solidification process in comparable conditions, and the reasons, causing the observed fragmentation effect was analyzed. For this purpose, instead of aluminum, the pure gallium was selected as a model melt, due to its much lower melting temperature (approx. 30 °C), which allowed us to simplify the experimental set-up. Visualization of the process enabled us to observe the in-situ formation of metal ingots, and what is more important – to evaluate their macro-crystalloid structure.

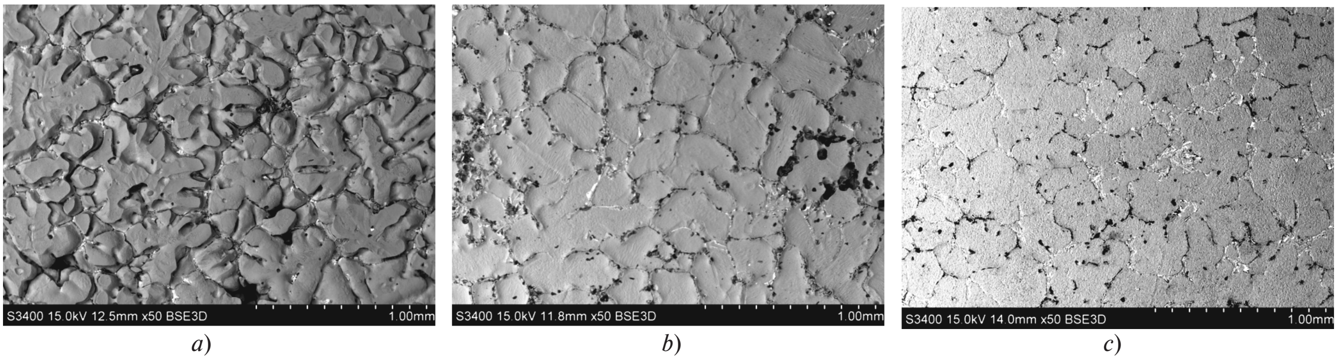
Visualization of a solidification process

This part of the investigation is based on experiments performed at the Swiss spallation neutron source SINQ, Paul Scherrer Institute, Villigen, Switzerland with use of NEUTRA facility [9]. Figure 2 depicts the experimental installation, optimized to work with the beam of thermal neutrons. For this, the setup was designed to have a quasi-two-dimensional form. Here (*1*) – is the heating system, serving for reduction of heat losses from the melt free surface and for increasing the temperature gradient; (*2*) – the window-glass vessel with copper bottom for the better heat transfer to the cooling system (*7*); (*3*) – pure gallium, preliminary melted and warmed up until 40 °C. A rectangular volume of the liquid had the height of 12 cm, the width of 10 cm and the depth of 2 cm. The induction system (*4*) produced a travelling magnetic field (TMF), consisted from three-phase coils with a phase shift of 60° and was feed with alternating current at 100 Hz and at 0.89 A of its effective value. The electric current density (j), following the phase shift in a three-phase induction coil, created a three-phase alternating magnetic field (B) and induced a current density (j_{ind}) in the metal. The interaction between the current in the coils and the current induced in the melt gave rise to the Lorentz force (*5*):

$$F_{EM} = j_{ind} \times B, \qquad (1)$$

which followed the traveling field and pulled the liquid after. In such conditions, the melt flow had a form of two oval vortices, with streamlines, indicated in Fig. 2 as (*6*), with the maximum vertical velocity on the vessel's axis (characteristic velocity) V_{ch} =18 mm/s on the vessel's axis.

In the experiment the application of TMF was realized in two ways – metal solidification in conditions of permanent and resonant pulsed EM stirring. Based on the characteristic velocity of the melt circulation and characteristic length, the resonant frequency of the pulsed TMF was calculated and had a value of f_{ch} =0.52 Hz. Thus the frequency of pulsed applied TMF was chosen to be close to this value – f_p =0.5 Hz. Here fp identifies the frequency of



a) *b*) *c*)

Fig. 1: The structure of specimens solidified in natural conditions (*a*), stirred with permanently applied AMF (*b*) and pulsed resonant AMF (*c*). Magnification is ×50

connection/disconnection the induction coils form the generator and determined by the sum of the on-time Tact and off-time T_0 (2):

$$f_p = 1/T_p;\ T_p = T_{act} + T_0. \tag{2}$$

The periodic modulations of the magnetic field lead to the appearance of the Lorentz force with pulses. In such a manner the stirring with permanently employed TMF can be described with the value of $f_p = 0$ Hz ($T_{act} = \infty$). As a reference case, the solidification process in natural conditions (without magnetic field) was considered. In Figure 3 are shown the images of three ingots, solidified in described arrangements. The original frame size of each image is 10×12 cm. The analysis of a macro-crystalloid structure was based on the optical local skeletonization of obtained images of ingots.

As it can be seen in Fig. 3, the type of the melt motion, having a direct influence on thermal conditions, led to the formation of different metal macro-structures. The ingot, grown in natural conditions has a big amount of short branches with various directions (some of them are skeletonized in Fig. 3,*a*). Based on the solidification theory [10], such a structure is assumed to be caused by the existence of more than one (additionally to the artificially applied) temperature gradients. Inhomogeneity in the temperature field provoked a growth of crystal branches, which due to different directions disturbed each other's growth and provided an accumulation of dislocations.

An opposite picture can be observed in Fig. 3,*b*, where the solidifying melt was stirred with resonant pulsed TMF. Here most of the branches have the extended length and a direction along the main temperature gradient, indicating a uniform heat transfer from the liquid phase. At the same time, the macro-structure of the ingot solidified in conditions of permanent stirring (Fig. 3,*c*), demonstrates a middle situation — the majority of branches having a growth direction along the main temperature gradient, formed shorter structures. Since all other conditions of the solidification process were the same, one can suggest, that the heat transfer conditions were strongly influenced by the type of melt motion.

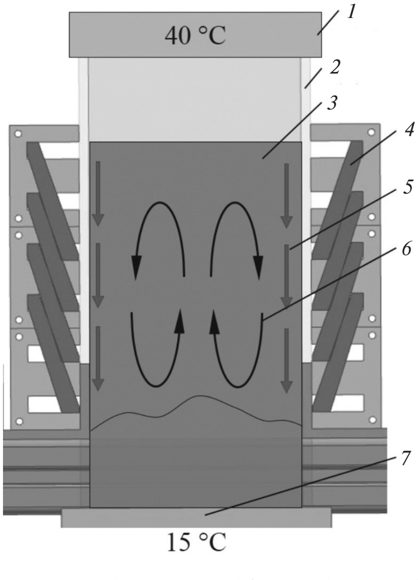


Fig. 2: The experimental system, used for visualization of EM-stirred solidifying pure gallium by means of neutron radiography

As it was shown in previous investigations, the pulsed application of magnetic field in accordance with the characteristic frequency of melt circulation is capable to increase the pulse component of the axial velocity considerably [11]. Taking into account the assumptions of other authors [12, 13], that in melt flows of such a configuration an axial component of velocity plays a key role in the heat exchange, one can state better heat transfer conditions and more homogenous temperature distribution, leading to the observed macro-structure. In the case of steady application of TMF, the heat transfer is intensified as well, but into a lesser extent. Same phenomena took place in the previous solidification experiment and became a reason of Al-alloy grain fragmentation. Although, on the micro-scale, in addition to the intensified heat transfer in the liquid, the intensive interaction between growing crystals and turbulent flows has a great influence as well.

Summary

One of the most important engineering problems is an optimal application of electromagnetic (EM) stirring for processing advanced metallic materials. One of the promising methods of EM stirring is the application of a resonant pulsed EM field to a solidifying melt, which compared to other methods provides the effective grain fragmentation without an increase of the energy consumption on the process. It is shown, that the resonant application of EM field leads to a considerable increase of velocity pulsations in a melt, in their turn changing heat transfer conditions to optimal for a formation of homogenously distributed metallic grains with a reduced size. In the present study, an application of neutron radiography for in-situ observation of a solidification process under the influence of permanent and pulsed EM stirring is considered. An increased volume of a crystallizing melt

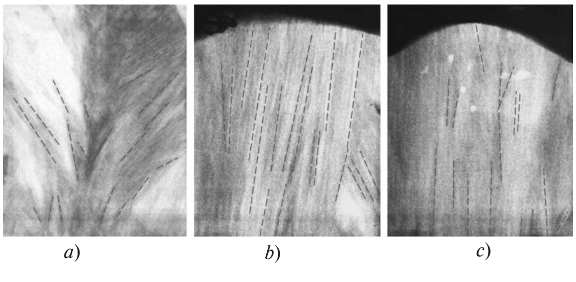

a) *b*) *c*)

Fig. 3: The visualized macro-crystalloid structure formed in natural conditions (*a*), stirred with resonant pulsed TMF (*b*) and with steadily applied TMF (*c*). Images demonstrate ingots on 150th-minute from the solidification begin

is investigated, where EM stirring leads to the development of three-dimensional turbulent flows. The principle of beam particles attenuation depending on the material density, used in neutron radiography, allowed us to observe the ingots evolution process and their skeleton structure, influenced by different treatments. The visualization has shown a strong influence of EM stirring, comparing to the solidification in natural conditions – stirred specimens gained a regular macro-structure, evidencing more stable heat transfer conditions. The most pronounced effect was obtained for the application of resonant stirring.

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Перемешивание расплава в процессе затвердевания для эффективной фрагментации зерна с использованием импульсных электромагнитных полей

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В статье описаны результаты экспериментального исследования, демонстрирующие и объясняющие эффект фрагментации зерна, вызванного импульсным резонансным электромагнитным перемешиванием. В эксперименте расплав 6082 из алюминиевого сплава был направленно отвержден под воздействием непрерывного и импульсного приложения переменного магнитного поля (AMF). Частота приложенного импульсного поля (PMF) соответствовала низкочастотной циркуляции расплава и вызывала резонансное увеличение импульсной составляющей скорости расплава. Структура образцов с электромагнитным перемешиванием сравнивалась со структурой, отвержденной в отсутствие магнитного поля. Был отмечен сильный эффект фрагментации (уменьшение среднего размера зерна на 51% по сравнению с затвердеванием в естественных условиях) для случая резонансного электромагнитного перемешивания. Кроме того, для анализа влияния потока, возникающего вследствие резонансного перемешивания, наблюдалось образование границы раздела «твердое тело-жидкость» и макрокристаллоидной структуры во время затвердевания непрерывно и импульсно перемешиваемого расплава с применением нового метода нейтронной радиографии. Результаты подтвердили сильное влияние импульсной составляющей скорости на тепловые условия во время затвердевания и, следовательно, структуру металла.

Ключевые слова: расплав, электромагнитное перемешивание, затвердевание, фрагментация зерна, визуализация процесса, нейтронная радиография

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